Cross-Layer Routing and Multiple-Access Protocol for Power-controlled Wireless Access Nets

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***Abstract-* Transmission power control in wireless communication network is used to attain network throughput increase, energy conservation, or provide for quality of service (QoS) support. We consider ad hoc wireless networks that are configured as Mobile Backbone Networks (MBNs). A hierarchical network architecture is synthesized, consisting of Access Nets (Anets) and Backbone Nets (BNets). Each ANet is managed by (dynamically elected) Backbone Nodes (BNs) that are equipped with higher capability (transmission and processing) modules. The BNs are chosen from currently active mobile backbone-capable nodes, or are represented by (ground and/or airborne) unmanned vehicles (UVs) that are guided into selected positions. In this paper we investigate a combined cross-layer protocol for routing and multiple access (MAC) for an MBN access net (Anet). In an ANet, the user nodes are associated with a BN that serves to allocate and manage their network layer (routing path) and MAC layer (time slot transmission) resources. Our new integrated protocol allows the net BN to instruct the ANet nodes to make power control adjustments while simultaneously allocating to them slots for the requested transmission of their packets. At the same time, a routing path is selected, so that a node may transmit its packet directly to the destination, or rather use the BN to relay this packet to a co-located destination node. We show this algorithm to lead to significant increase in the net throughput level through spatial reuse of the access net communications resources. Our scheme also strives to reduce power and energy requirements in that nodes only employ the power levels required to reach their designated destination (or next hop). Furthermore, the protocol tends to reduce employed power levels to achieve higher spatial reuse factors. In addition, through the use of resource (including time, frequency, or CDMA slots) allocations to identified user packet flows or real-time streams, we are able to provide quality of service guarantees for selected group of flows.**

Key words- power control; MAC; routing; ad hoc wireless networks; mobile backbone network.

[1] This work was supported by Office of Naval Research (ONR) under Contract No. N00014-01-C-0016, and by the National Science Foundations under Grant No. ANI-0087148.

I. INTRODUCTION

Transmission power control in wireless communication networks has been used for a multitude of purposes, including capacity upgrades, increase of topological robustness to node/link failures, energy conservation, extension of network lifetime, and for quality of service (QoS) support. Recent results have shown that by applying optimal power control in an ideal medium access protocol, the aggregate channel utilization can be improved by a factor of $O(\sqrt{\rho})$, where ρ is the node density in the network [6].

Current work on power control can be loosely categorized into three classes: power controlled topology synthesis ([2],[3],[4]), and power controlled multiple access ([5],[8],[10],[18]), and power aware routing. ([11],[12],[13]). Paper [2] introduces an adaptive clustering mechanism using transmission power on the performance of ah hoc networks. The COMPOW protocol introduced in [3] asymptotically maximizes capacity and supports connectivity of the network. This protocol suggests the reduction of the common power level to the lowest value at which the network remains connected. Paper [4] considers the assignment of different transmit powers to different nodes to meet a global topological property (connectivity and bi-connectivity) in the context of ad hoc networks. In [5], a power controlled multiple access MAC protocol is proposed for ad hoc networks. This protocol is based on the use of CSMA/CA MAC protocol and is designed to maximize channel spatial reuse. In [8], a power controlled multiple access (PCMA) protocol is introduced for supporting packetized data traffic in static wireless networks. Under this protocol, the power level optimization for every transmitter is based on both its backlog level and the observed local interference. Paper [10] proposes a power controlled multiple access protocol with the purpose of conserving power consumption. In papers [11],[12], and [13] different methodologies for power aware routing are proposed. A number of algorithms have been studied involving spatial reuse time division multiple access (STDMA) without power control. They employ schemes that can be categorized as node scheduling ([7],[17]) or link scheduling ([16]) oriented.

In this paper, we study a mobile wireless access network. Such networks form the lower hierarchy of an ad hoc wireless network that is architectured as a Mobile Backbone Network (MBN) [1], [14]-[15]. A hierarchical network architecture is synthesized, consisting of Access Nets (ANets) and Backbone Nets (BNets). Each ANet is managed by a (dynamically elected) Backbone Node (BN) that is equipped with higher capability modules. The BNs are chosen from currently active mobile backbone-capable nodes, or are represented by (ground and/or airborne) unmanned vehicles (UVs) that are guided into selected positions.

We investigate a combined cross-layer protocol for routing and multiple access (MAC) for an MBN access net (ANet). In an ANet, the user nodes are associated with a BN that serves to allocate and manage their network layer (routing path) and MAC layer (say, time slot transmission) resources. Our new integrated protocol allows the net BN to instruct the ANet nodes to make power control adjustments while simultaneously allocating to them slots for the requested transmission of their packets. Clearly the BN is used as a focal point for packet transmissions between ANets (through a BNet). For intra-ANet local traffic, at the same time that a slot is allocated to the transmitting node, a routing path is selected, so that a node may transmit its packet directly to the local destination or rather use the BN to relay this packet to the destination node.

While the underlying system assumes that individual nodes are not primarily guided in their actions by their attempt to reduce expanded energy levels, our selected routes will tend to reduce employed power levels to attain higher spatial reuse levels, and will thus also contribute to energy conservation.

We present three heuristic algorithms for joint power controlled multiple access control integrated with routing in an ANet. We compare these heuristics from throughout point of view through simulation. In addition, we investigate the effect of node density and availability of different power levels on throughout in our simulations. Further, we examine the trade-off between prioritizing a subset of packets and the overall throughout.
The rest of the paper is organized as follows. In section II, we introduce the system assumptions. The interference model is elaborated in section III. We analyze the system from power control, routing, and slot allocation point of view, in section IV. In section V, we introduce the ANet

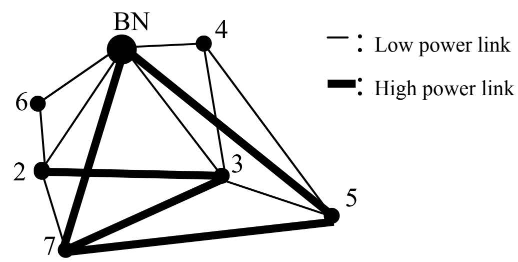

Figure 1. An ANet with two power levels.

power controlled multiple access (APCM) algorithm. Finally, in section VI, we present our simulation results.

II. SYSTEM ASSUMPTIONS

A mobile backbone network (MBN) topological structure is composed of Access nets (ANets) and a backbone network (Bnet)[1]. An ANet is composed of regular nodes (RNs) and a single backbone node (BN)(Fig.1). All nodes in an ANet have identical half-duplex radios with omni-directional antennas that allow them to transmit at m different power levels. Each regular node can reach its associated backbone node at a properly selected (sufficiently high) power level.

We study here the design of a joint power controlled demand-assigned time-division multiple-access (DA/TDMA) medium access control (MAC) scheme combined with a routing protocol for a single ANet. Note that a demand-assigned scheme that jointly (or individually) allocates time, frequency, and code assets is similarly handled. We assume that each transmitter that is allocated a time slot operates at a selected power level (chosen to be sufficient to reach its destination and avoid unallowable interferences) at a fixed data rate, of say *R* [bits/sec]. We aim to achieve a high throughput level. Noting the net throughput to be determined by the factor *R*SRF/L*, where *SRF* denotes the net's spatial reuse factor and L represents the average path length (measured in hops), it is of interest to achieve a high *SRF/L* ratio.

The distances between every pair of nodes in an ANet (or equivalently their coordinates) are known by the BN. We assume that these inter-nodal distances can be used as an approximate (yet sufficient) measure of reachability. At every time slot one or more packets are unicasted toward their destinations. Every node can individually adjust its transmission power on a per packet basis. To simplify the routing operation, we further assume for the current study, that (in an ANet) only the BN can play the role of a packet relay. The BN acts as the central controller and manager for the ANet.

We denote the *packet request matrix* composed at the BN as R_ψ, where $R_\psi = \{R_\psi(i,j)\}$ and $R_\psi(i,j)$ represents the number of packet transmission requests corresponding to packets that will be available for transmission from source i to destination j at the start of the $\psi - th$ timeframe. These requests include the newly generated packet transmission requests and packet request backlogs that have not been assigned by previous allocations. The packet generation matrix R_Ψ is composed in the BN at the start time of the $\psi - th$ timeframe through the establishment of a control multiple access channel (based on an embedded random access channel used by nodes to initially send request control packets to the BN, and subsequently the use of piggybacking of request packets in assigned slots).

The request matrix can be processed at the BN to achieve fairness, provide for flow and congestion control or attain QoS based performance (e.g., by using weighted fair queuing or PGPS based queue-ordering and scheduling of nodal requests, based on recording the resources allocated to nodes over a sliding window of length of *W* slots, and using packet's Class/Type of Service differentiating indicators, or reservation based admission control setups). Requests are considered for store-and-forward service by allocating slots for the transmission of individual packets, as well as for real-time service whereby slots are allocated periodically to assign a real-time channel to a node at a requested rate for the duration of its activity.

III. INTERFERENCE MODEL

Assume node *x* in the ANet to transmit a packet at power level P_k and also assume that there is no other transmission in the network at this time slot. We define L_k as the distance from a transmitting node operating at power level P_k at which the received power factor $P_k/(L_k)^\beta$ is equal to a constant *C*, whereby β is the path loss ratio factor. All nodes that are within a distance L_k from such a transmitting node are able to receive the packet successfully, $k=1,2,\ldots,m$, provided that no other transmissions are scheduled at the same time by nodes located within a prescribed distance (see below) from the receiving node. Now, consider the case that other receivers may be targeted for packet receptions from different transmitters at the same time slot. For the transmission originating at node *x* to not interfere with the intended transmission of these other receivers, we assume that the latter receivers must be at a distance from *x* that not only surpasses L_k but also surpasses L'_k, where $L'_k > L_k$. The inclusion of the two sets of distances provides for the distinction between the received power level required for a successful reception of a packet and the corresponding (usually lower) power level that induces interference with another packet reception.

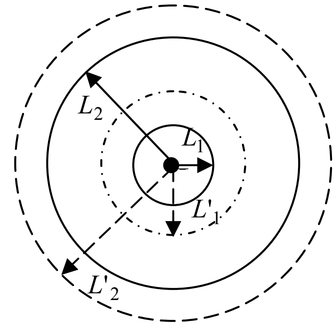

Figure 2. Communication and interference ranges associated with two power levels.

Thus, when node *x* transmits a packet at the *k-th* power level to node *y*, this transmission is successfully received by *y* if:

1. The distance between *x* and *y* is no more than L_k, i.e.
$$d(x,y) \;\le\; L_k d(x,y) \;\le\; L_k \tag{1}$$

and

2. For every other node *z* simultaneously transmitting at the *r-th* power level,
$$d(z,y) \;>\; L'_r\,. \tag{2}$$

We denote L_k and L'_r as the *communication range* and *interference range* associated with the k-th and r-th power level, respectively (Fig. 2). We define the *interference-communication ratio (I-C ratio)* as $\alpha = L'_k / L_k$, $k=1,2,\ldots,m$. Though, α and the average spatial reuse factor are inversely proportional, we do not consider any constraint (such as an upper bound on α). However, we assume that $\alpha \ge 1$, which is the case in most practical cases. Note that the above-mentioned interference model is a generalization of the Protocol interference model presented in [6] and [7]. In the rest of the paper, we denote a transmission from node *i* to node *j* by $i \to j$.

IV. SYSTEM DESCRIPTION:

As indicated before, the APCM algorithm simultaneously allocates time slots, adjusts transmission power levels, and determines routes for packet transmission requests, in order to maximize the ANet's overall throughout. In the following, we individually illustrate our underlying model from power adjustment, routing, and slot allocation perspectives.

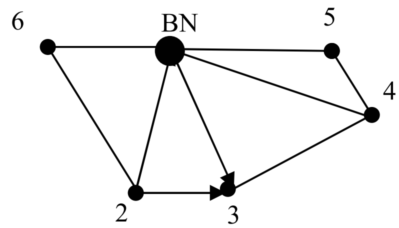

Figure 3. Two different routes for transmission form source 2 to destination 3.

A. Power Assignment

We denote the power of direct transmission from node i to node j in time slot Λ by $P_{ij}(\Lambda)$, $i \neq j$, $i,j = 1,2,...,n$, $\Lambda = 1,2,...,M$. Based on inequality (1) and providing that $L_{k-1} < d(i,j) \leq L_k$, in order to have a successful transmission from i to j, we need

$$P_{ij}(\Lambda) \geq P_k, \quad k = 1,2,\cdots,m, \Lambda = 1,2,\cdots,M, \tag{3}$$

where we set $L_0 = 0$. Note that by selecting $P_{ij}(\Lambda)$ to be strictly greater than P_k, we can only reduce the spatial reuse factor while expanding higher energy levels. Therefore, we impose *the per link minimality constraint* on $P_{ij}(\Lambda)$'s so that we set

$$P_{ij}(\Lambda) = P_k, \quad k = 1,2,\cdots,m, \Lambda = 1,2,\cdots,M. \tag{4}$$

As a result, in our model, $P_{ij}(\Lambda)$ will be independent of Λ and for every individual transmission the power is selected to a minimum required level. Note that the latter constraint is a generalization of *the per node minimality constraint* presented in [4].

B. Routing

Assuming the BN power and processing/switching resources to be significantly higher than those of the other nodes, we permit only the BN to act as a relay. Hence, for every transmission $i \rightarrow j$ for which either i or j designates the BN, the route simply consists of a single hop. When neither the source nor the destination is the BN, two alternative routes are considered: direct transmission from the source to the destination (if feasible) or indirect 2-hop route from the source to the destination that passes through the BN (Fig. 3).

As noted before, to attain high throughput one needs to maintain a relatively high spatial reuse factor (*SRF*) to average path length ratio. Hence, an indirect route between a given source destination pair of nodes is preferable only if it contributed to commensurate increase in the *SRF* (to compensate for the longer path length).

C. Time Slot Allocation

Assume every timeframe to include M time slots. We are interested in producing at the start of each timeframe a schedule that allocates slots over the current timeframe, which maximizes the Anet throughput level, thus maximizing the long-term average number of successful (non interfering) receptions (by the packets' ultimate destinations) per slot.

Clearly, this joint power-control/routing/slot-allocation is a challenging combinatorial problem. In general, calculating an optimal allocation schedule solution is not computationally practical. In fact, the slot allocation problem with even a single power level is by itself known to be an NP-hard problem [9].

V. THE ANET POWER CONTROLLED MULTIPLE ACCESS ALGORITHMS (APCM)

We represent the ANet by graph $G(V,E)$, where V is the set of nodes in the ANet and E is the set of communication links between the nodes. Let's consider the Ψ -th timeframe. For this timeframe, recall that $R_\Psi(i,j)$ represents the number of outstanding requests at the start of the Ψ -th timeframe for transmissions from source i to destination j. Each such a request for a single packet transmission from source i to destination j is identified as an *(i,j) transmission request.*

The *r-th (i,j) transmission request* can be satisfied by assigning it to either a direct single hop path or to a two-hop path that passes through the BN. In the former case, we identify the transmission option *(i,j,r)*. In the latter case, this transmission request induces two *transmission options*: An $i \rightarrow BN$ transmission option that is labeled as *(i,BN,r,j)*, followed by an $BN \rightarrow j$ transmission option that is labeled as *(BN,j,r,i)*. Thus, in considering the scheduling of transmission requests, we evaluate for each such request the above mentioned associated transmission options.

Definition 1: We define V'_1 as the set of transmission options corresponding to *(i,j)* transmission requests where either $i=BN$ or $j=BN$. Each member is labeled as transmission option *(i,j,r)*, $r=1,2,..., R_\Psi(i,j)$.

Definition 2: We define V'_2 as the set of transmission options corresponding to *(i,j)* transmission requests for which $i \neq BN$, $j \neq BN$, and $d(i,j) > L_m$. To realize such requests, we include the $i \rightarrow BN$ transmission options, labeled as *(i,BN,r,j)*, $r=1,2,...,$ $R_\Psi(i,j)$; and $BN \rightarrow j$ transmission options, labeled as *(BN,j,r,i)*, $r=1,2,...,$ $R_\Psi(i,j)$.

Definition 3: We define V'_3 as the set of transmission options corresponding to *(i,j)* transmission requests for which $i \neq BN$, $j \neq BN$, and $d(i,j) \leq L_m$. To realize such requests, we include the *i→BN* transmission options, labeled as *(i,BN,r,j), r=1,2,…,* $R_\Psi(i,j)$; the *BN→j* transmission options, labeled as *(BN,j,r,i), r=1,2,…,* $R_\Psi(i,j)$, and direct transmission options that are labeled as *(i,j,r), r=1,2,…,* $R_\Psi(i,j)$.

We denote the weighted Interference Graph by $G'(V',E')$, where $V' = V'_1 \bigcup V'_2 \bigcup V'_3$ is the set of nodes in G' and E' is the set of edges connecting nodes in V'. There exists an edge between two transmission options iff they cannot be simultaneously received in their associated destinations successfully under the per link minimality constraint. The weight of every node (transmission option) labeled as *(i,j,r)* or *(BN,j,r,i)* is set equal to 1. The weight of every node (transmission option) labeled as *(i,BN,r,j)* is set equal to 0.

Now, the joint power control/routing/slot allocation problem can be defined as a special coloring of graph G'. Recall that the classical graph coloring problem is defined as the minimization of number of colors used for coloring all nodes of the graph [19]. Our underlying problem can be defined as maximization of weight of the colored nodes of graph G' given a finite set of colors, under the following two constraints:

1. Node *(BN,j,r,i)* can be colored iff node *(i,BN,r,j)* has been already colored, $\forall (BN,j,r,i),(i,BN,r,j) \in V'_2 \bigcup V'_3$.
2. In every coloring of graph G', if node *(BN,j,r,i)* is colored, node *(i,j,r)* should be uncolored and vice versa, $\forall (BN,j,r,i),(i,j,r) \in V'_3$.

To differentiate between the classical coloring and the above coloring of a graph, we denominate the latter as "partial coloring".

By definition [20], *Sequential Greedy Coloring Heuristics* (SGCH) are the heuristic algorithms for the classical graph coloring problem, whereby extend a partial coloring by successively augmenting the number of colored vertices. In SGCH, once a color is assigned to a vertex, it will not change. The quality of the coloring provided by SGCH depends on the ordering of the vertices. The *Color List* and/or the *Vertex List* are either pre-ordered before the application of SGCH or re-ordered during the application of SGCH. There is no known ordering scheme that is superior over all other ordering schemes. However, it is known that for every graph G, there always exists an ordering of the vertices such that the application of SGCH to the ordering will find an optimal coloring.

We can loosely classify different sequential greedy coloring algorithms in the literature that have been applied to the scheduling problem as follows:

1. ***Transmission-Oriented Sequential Algorithms (TOSA):*** In this class of algorithms once a transmission cannot be assigned to a particular slot, the algorithm will examine the (possible) next slot in the list for allocation to the same transmission. These algorithms correspond to the "Longitudinal Movement" through the timeframe.

2. ***Slot-Oriented Sequential Algorithms (SOSA)*****:** In this class of algorithms once a transmission cannot be assigned to a particular slot, the algorithm will examine the (possible) next transmission in the list for assignment to the same slot. These algorithms correspond to the "Latitudinal Movement" through the timeframe.

3. ***Synthetic Sequential Algorithms (SSA):*** In this class of algorithms once a transmission cannot be assigned to a particular slot, the algorithm may examine the allocation of a slot to a transmission, whereby both the transmission and the slot are different from the previous step. These algorithms are associated with "Diagonal Movement" through the timeframe.

Remark: In each of the above classes, the Time Slot List (Color List) and/or the Transmission List (Node List) can be sorted in a pre-ordered or re-ordered fashion.

In the following, we examine three heuristics for partial coloring of graph G'. Each of these coloring schemes is associated with one of the above-mentioned classes:

In TOSA, the Time Slot List consists of the M time slots in the underlying timeframe sorted based on the number of transmissions that have been heretofore allocated to each of the slots (with the slot allocated the least number of transmissions delegated to the top of the list). All unassigned transmission options are sorted in the Transmission Option List based on their degree in the residual Interference Graph (with the transmission option that has the minimum degree delegated to the top of the list.) The Time Slot List and the Transmission Option List are both re-sorted after every time slot allocation.

In the *k-th* step of SOSA, we heuristically find the minimum edge covering set associated with the induced subgraph $< V' - \sum_{j=1}^{k-1} MIS_j >$ of Interference Graph G', where MIS_j is the maximum independence set associated with the *j-th* step of the algorithm. The complement of the minimum edge covering set is a maximum independent set and corresponds to the transmissions assigned to slot *k*.

Let's denote the unassigned transmissions that prior to the current assignment could have been allocated to slot *j* by V_j''. At every step of SSA, we allocate transmission option *u* to slot *v* if the following equality is satisfied:

$$w(u,v) = \min_{i \in V_j''} \min_{j \in \{1,\cdots,M\}} w(i,j)\,, \tag{5}$$

where

$$w(i,j) = \sum_{k \in <V_J''-\{i\}>} \frac{1}{1+d_k}\,, \tag{6}$$

and by <*A*>, we mean the induced subgraph of $<V_j''-\{i\}>$ of Interference Graph G'. We utilize *w(i,j)* as an estimate for the dimensionality of a maximum independent set (independence number) of the Interference Graph G' induced by $V_j''-\{i\}$ [21].

VI. SIMULATION RESULTS

In our simulation environment, the regular nodes have a uniform distribution in a circle with radius of L_{max}, whose center is the backbone node. The packet generation is based on a Poisson arrival process with the intensity of λ packets per slot for every source-destination transmission. The ANet includes 10 nodes (1 backbone node and 9 regular nodes), with the path loss ratio of 2.2 and the I-C ratio of 1.1. Every timeframe is assumed to be composed of 10 slots.

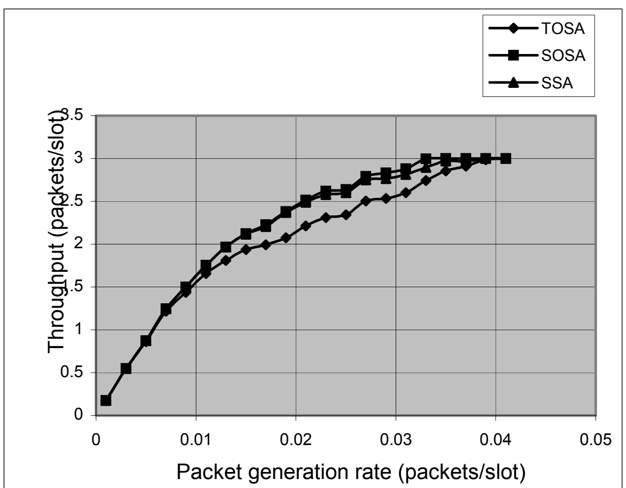

Figure 4. Throughput comparison among three heuristics

In Figure 4, TOSA, SOSA, and SSA are compared with each other, using four transmission power levels (1mW, 10mW, 50mW, and 100mW). Note that SOSA, closely followed by TOSA, always has the highest throughput.

In all three heuristics, the throughput asymptotically converges to a positive integer as the packet generation rate increases. This integer is equal to the cardinality of the maximum independent set (independence number) of the randomly generated topology, under the given set of power levels, i.e. {1mW, 10mW, 50mW, and 100mW}. This is due to the fact that during the steady state and under relatively high packet generation rates, sufficient amount of packets that are associated with the maximum independent set always exists.

In Figure 5, we depict the effect of different availability of transmission power levels on the overall throughout of the ANet. For this analysis, five types of radios have been taken into consideration: radios with a single power level (100mW), radios with two power levels (50mW, 100mW), radios with four power levels (1mW, 10mW, 50mW, 100mW), radios with 10 power levels (1mW, 10mW, 20mW, 30mW, 50mW, 60mW, 70mW, 80mW, 90mW, 100mW), and radios with continuous power level adjustment capability. Finally, in Figure 6, we demonstrate the ability of our protocol to support the prioritization of certain transmissions and exemplify the throughput decrease involved.

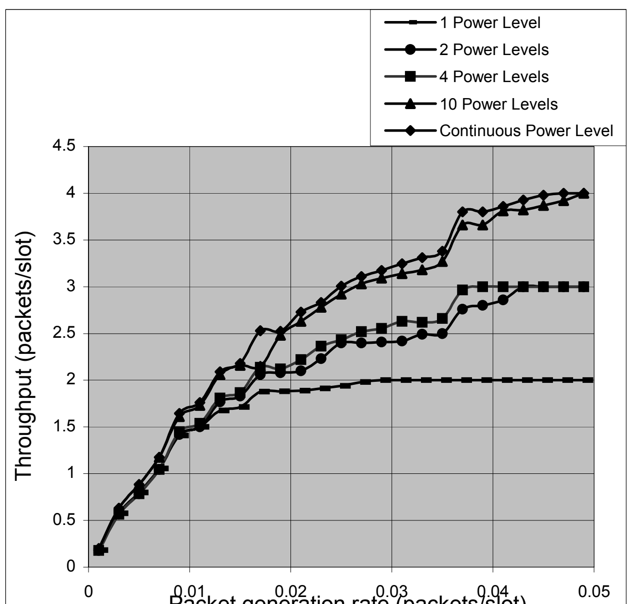

Figure 5. The effect of availability of different power levels

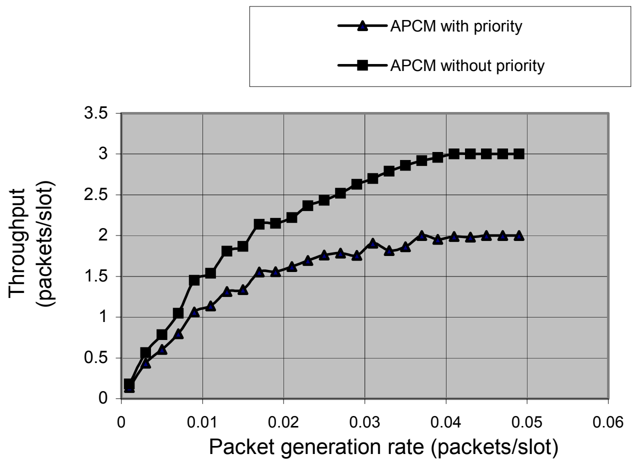

Figure 6. The effect of prioritization on the ANet overall throughput

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